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Search for Lepton Flavor Violating τ Decays into Three Leptons

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Abstract

We search for lepton-flavor-violating τ decays into three leptons (electron or muon) using 535 fb^{-1} of data collected with the Belle detector at the KEKB asymmetric-energy e^+e^- collider. No evidence for these decays is observed and we set 90% confidence level upper limits on the branching fractions between 2.0×10^{-8} and 4.1×10^{-8}. These results improve the best previously published upper limits by factors from 4.9 to 7.0.

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INTRODUCTION

Lepton flavor violation (LFV) appears in various extensions of the Standard Model (SM), e.g., supersymmetry (SUSY), leptoquark and many other models. In particular, lepton-flavor-violating decays into $\tau^- \to \ell^-\ell^+\ell^-$ (where $\ell = e$ or μ) are discussed in various SUSY models [1, 2, 3, 4, 5, 6, 7], models with little Higgs [8, 9], left-right symmetric models [10] as well as models with heavy singlet Dirac neutrinos [11] and very light pseudoscalar bosons [12]. Some of these models with certain combinations of parameters predict that the branching fractions for $\tau^- \to \ell^-\ell^+\ell^-$ decays can be as high as 10^{-7}, which is already accessible in high-statistics B factory experiments. Searches for LFV τ decays into three leptons have a long history [13], which starts from the pioneering experiment of MARKII [14]. In previous high-statistics analyses, both Belle and BaBar reached 90% confidence level (C.L.) upper limits on the branching fractions of the order of 10^{-7} [15, 16], based on about 90 fb^{-1} of data. Here, we update our previous results using 535 fb^{-1} of data collected with the Belle detector at the KEKB asymmetric-energy e^+e^- collider [17], taken at the $\Upsilon(4S)$ resonance and 60 MeV below it.

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL), all located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside the coil is instrumented to detect K_{L}^0 mesons and to identify muons (KLM). The particle identification is based on the ratio of the energy deposit in the ECL to the momentum measured in the SVD and CDC, the shower shape in the ECL, the particle range in the KLM, the hit information from the ACC, the dE/dx information in the CDC, and the particle time-of-flight from the TOF. The detector is described in detail elsewhere [18]. The leptons are identified using likelihood ratio, ($\mathcal{P}(e)$) for electrons [19] and ($\mathcal{P}(\mu)$) for muons [20], which are based on electron and muon probabilities, respectively.

In order to estimate the signal efficiency and to optimize the event selection, we use Monte Carlo (MC) samples. The signal and the background events from generic $\tau^+\tau^-$ decays are generated by KORALB/TAUOLA [21]. In the signal MC, we generate $\tau^+\tau^-$, where a τ decays into three leptons and the other τ decays generically. All leptons from $\tau^- \to \ell^-\ell^+\ell^-$ decays are assumed to have a uniform angular distribution in the τ lepton's rest frame [22]. Other backgrounds including $B\bar{B}$ and $e^+e^- \to q\bar{q}$ ($q = u, d, s, c$) events, Bhabha events, $e^+e^- \to \mu^+\mu^-$, and two-photon processes are generated by EvtGen [23], BHLUMI [24], KKMC [21], and AAFHB [25], respectively. All kinematic variables are calculated in the laboratory frame unless otherwise specified. In particular, variables calculated in the e^+e^- center-of-mass (CM) system are indicated by the superscript "CM".

EVENT SELECTION

We search for $\tau^+\tau^-$ events in which one τ decays into three leptons (signal τ), while the other τ decays into one charged track, any number of additional photons, and neutrinos (tag τ). Candidate τ-pair events are required to have four tracks with a zero net charge. Thus, the decay chain to be reconstructed is:

$$\{\tau^- \to \ell^-\ell^+\ell^-\} \;\; + \;\; \{\tau^+ \to (\text{a track})^+ + (n \geq 0\ \gamma) + X(\text{missing})\}[\dagger].$$

Here, all possible combinations of three leptons in the signal τ decay, which include the $e^-e^+e^-$, $\mu^-\mu^+\mu^-$, $e^-\mu^+\mu^-$, $\mu^-e^+e^-$, $\mu^-e^+\mu^-$, and $e^-\mu^+e^-$ modes, are searched for. Because the background components differ between signal decay modes, the selections described below are optimized separately for each mode.

The event selection starts by reconstructing four charged tracks and any number of photons within the fiducial volume defined by $-0.866 < \cos\theta < 0.956$, where θ is the polar angle relative to the direction opposite to that of the incident e^+ beam in the laboratory frame.

The transverse momentum (p_t) of each charged track and energy of each photon (E_γ) are required to be $p_t > 0.1$ GeV/c and $E_\gamma > 0.1$ GeV, respectively. The distance of the closest point for each charged track with respect to the interaction point is required to be within ± 0.5 cm in the transverse direction and within ± 3.0 cm in the longitudinal direction.

The particles in an event are then separated into two hemispheres referred to as the signal and tag sides using the plane perpendicular to the thrust axis [26]. The tag side contains a charged track while the signal side contains three charged tracks. We require all charged tracks on the signal side to be identified as leptons. The electron (muon) identification criteria are $\mathcal{P}(e) > 0.9$ ($\mathcal{P}(\mu) > 0.9$) for the momentum greater than 0.3 GeV/c (0.6 GeV/c). The electron (muon) identification efficiency for our selection criteria is 91% (85%) while the probability to misidentify pion as electron (muon) is below 0.5% (2%).

To ensure that the missing particles are neutrinos rather than photons or charged particles that pass outside the detector acceptance, we impose additional requirements on the missing momentum vector $\vec{p}_{\rm miss}$, which is calculated by subtracting the vector sum of the momenta of all tracks and photons from the sum of the e^+ and e^- beam momenta. We require that the magnitude of $\vec{p}_{\rm miss}$ be greater than 0.4 GeV/c, and that its direction point into the fiducial volume of the detector.

To reject $q\bar{q}$ background, we require that the magnitude of thrust (T) be $0.90 < T < 0.97$ for all modes except for the $\tau^- \to e^-e^+e^-$ mode for which it should be $0.90 < T < 0.96$. We also require 5.29 GeV $< E^{\rm CM}_{\rm vis} <$ 9.5 GeV, where $E^{\rm CM}_{\rm vis}$ is the total visible energy in the CM system which is defined as the sum of the energies of three leptons, the charged track on the tag side (with a pion mass hypothesis) and all photon candidates.

Since neutrinos are emitted only on the tag side, the direction of $\vec{p}_{\rm miss}$ should lie within the tag side of the event. The cosine of the opening angle between $\vec{p}_{\rm miss}$ and the charged track on the tag side in the CM system, $\cos\theta^{\rm CM}_{\rm tag-miss}$, is therefore required to lie in the range $0.0 < \cos\theta^{\rm CM}_{\rm tag-miss} < 0.98$. The reconstructed mass on the tag side using a charged track (with a pion mass hypothesis) and photons, $m_{\rm tag}$, is required to be less than 1.777 GeV/c^2. As shown in Fig. 1, reasonable agreement between data and background MC is obtained in the distributions of $\cos\theta^{\rm CM}_{\rm tag-miss}$ and $m_{\rm tag}$.

Conversions ($\gamma \to e^+e^-$) are a large background for the $\tau^- \to e^-e^+e^-$ and $\mu^-e^+e^-$ modes. We require that the cosine of the opening angle between the direction of the e^+e^- pair and the other lepton in the CM system, ($\cos\theta^{\rm CM}_{\rm lepton-ee}$) be less than 0.90 if the invariant mass of the e^+e^- pair (M_{ee}) is less than 0.2 GeV/c^2 for these modes. As shown in Fig. 2 for the

[†] Unless otherwise stated, charge-conjugate decays are implied throughout this paper.

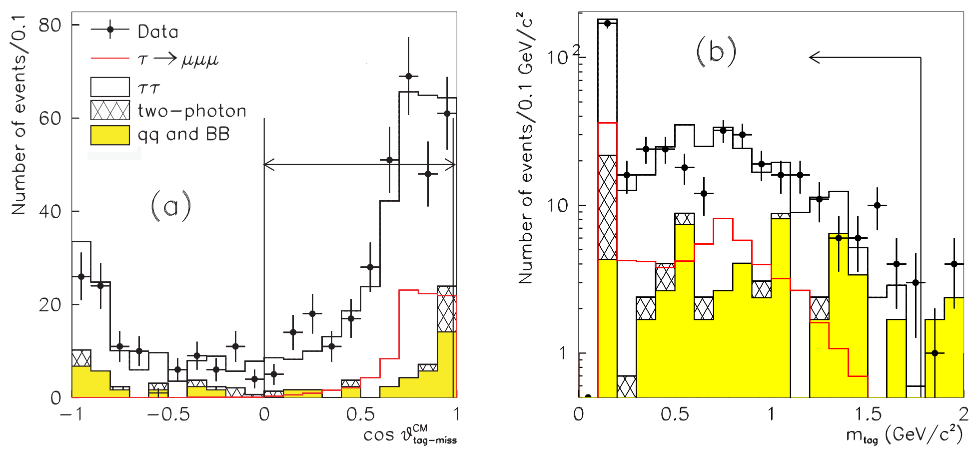

FIG. 1: Kinematic distributions used in the event selection: (a) the cosine of the opening angle between a charged track on the tag side and missing particles in the CM system ($\cos\theta^{\rm CM}_{\rm tag-miss}$); (b) the reconstructed mass on the tag side using a charged track and photons after $E^{\rm CM}_{\rm vis}$ and T event selection. While the signal MC ($\tau^- \to \mu^-\mu^+\mu^-$) distribution is normalized arbitrarily, the background MC are normalized to the same luminosity as that of data. Selected regions are indicated by the arrows from the marked cut boundaries.

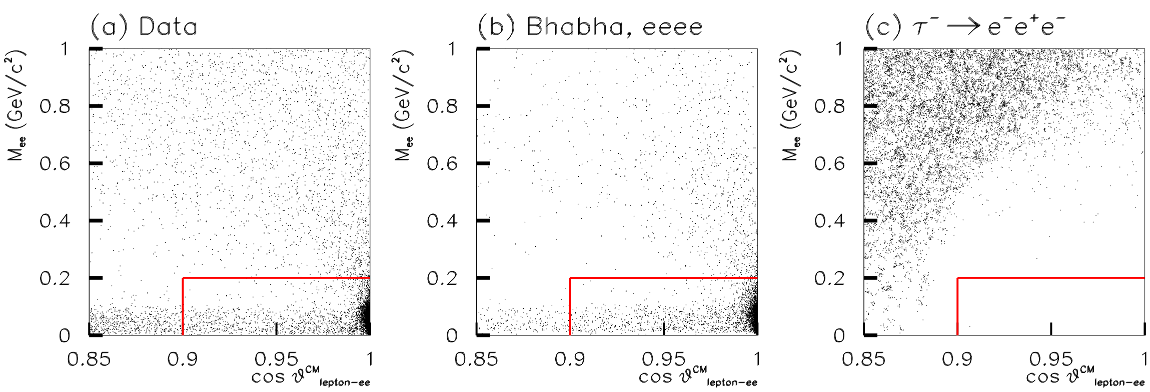

FIG. 2: Scatter-plots of the reconstructed invariant mass of the e^+e^- pair (M_{ee}) vs. cosine of the opening angle between the direction of the e^+e^- pair and the other electron ($\cos\theta^{\rm CM}_{\rm lepton-ee}$) for (a) data, (b) Bhabha and $eeee$, (c) signal MC ($\tau^- \to e^-e^+e^-$)

$\tau^- \to e^-e^+e^-$ mode (two entries from each event), the signal efficiency is not affected by this cut, while the large background from the conversions can be reduced.

For the $\tau^- \to e^-e^+e^-$ and $\tau^- \to e^-\mu^+\mu^-$ modes, the charged track on the tag side is required not to be an electron by applying $\mathcal{P}(e) < 0.1$ since a large background still remains from two-photon and Bhabha events. Furthermore, we reject the event if the charged track on the tag side is in gaps between barrel and endcap of the ECL. To reduce backgrounds from Bhabha and $\mu^+\mu^-$ events, we require that the momentum in the CM system of the charged track on the tag side be less than 4.5 GeV/c for the $\tau^- \to e^-e^+e^-$ and $\tau^- \to \mu^-e^+e^-$

TABLE I: The selection criteria for the missing momentum ($p_{\rm miss}$) and missing mass squared ($m^2_{\rm miss}$) correlations for each mode, $p_{\rm miss}$ is in GeV/c and $m^2_{\rm miss}$ is in (GeV/c^2)^2.

Mode	Hadronic tag mode	Leptonic tag mode
$\tau^- \to \mu^-\mu^+\mu^-$	$p_{\rm miss} > -3.0 m^2_{\rm miss} - 1.0$	$p_{\rm miss} > -2.5 m^2_{\rm miss}$
$\tau^- \to \mu^- e^+ e^-$	$p_{\rm miss} > 3.0 m^2_{\rm miss} - 1.5$	$p_{\rm miss} > 1.3 m^2_{\rm miss} - 1$
$\tau^- \to e^-\mu^+\mu^-$		
$\tau^- \to e^- e^+ e^-$	$p_{\rm miss} > -3.0 m^2_{\rm miss} - 1.0$	$p_{\rm miss} > -2.5 m^2_{\rm miss}$
	$p_{\rm miss} > 4.2 m^2_{\rm miss} - 1.5$	$p_{\rm miss} > 2.0 m^2_{\rm miss} - 1$
$\tau^- \to e^+\mu^-\mu^-$	N.A.	N.A.
$\tau^- \to \mu^+ e^- e^-$		

modes.

Finally, to suppress backgrounds from generic $\tau^+\tau^-$ and $q\bar{q}$ events, we apply a selection based on the magnitude of the missing momentum $p_{\rm miss}$ and missing mass squared $m^2_{\rm miss}$ for all modes except for $\tau^- \to e^+\mu^-\mu^-$ and $\mu^+ e^- e^-$. We do not apply this cut for the latter modes since backgrounds for them are much smaller. We apply different selection criteria depending on whether the τ decay on the tag side is hadronic or leptonic: two neutrinos are emitted if the τ decay on the tag side is leptonic, while one neutrino is emitted if the τ decay on the tag side is a hadronic one. Therefore, we separate events into two classes according to the track on the tag side: leptonic or hadronic. The selection criteria are listed in Table I; the distributions of $m^2_{\rm miss}$ and $p_{\rm miss}$ for hadronic and leptonic decays are shown in Fig. 3.

SIGNAL AND BACKGROUND ESTIMATION

The signal candidates are examined in the two-dimensional plots of the $\ell^-\ell^+\ell^-$ invariant mass ($M_{3\ell}$), and the difference of their energy from the beam energy in the CM system (ΔE). A signal event should have $M_{3\ell}$ close to the τ-lepton mass and ΔE close to zero. For all modes, the $M_{3\ell}$ and ΔE resolutions are parameterized from fits to the signal MC distributions with an asymmetric Gaussian function that takes into account initial state radiation. The resolutions of $M_{3\ell}$ and ΔE for each mode are summarized in Table II.

To evaluate the branching fractions, we define elliptical signal regions determined from fits to the $M_{3\ell}$ and ΔE distributions as shown in Table II. These signal regions are optimized by signal MC, so that 90% of the signal events that passed all the selections are contained in the signal region.

We blind the data in the signal region and estimate the signal efficiency and the number of the backgrounds from the MC and the data outside the signal region, so as not to bias our choice of selection criteria. Figure 4 shows scatter-plots for the data and the signal MC distributed over $\pm 20\sigma$ in the $M_{3\ell} - \Delta E$ plane. No events are observed outside the signal region for any modes except for $\tau^- \to e^- e^+ e^-$ in which four events are found. The remaining background events in the $\tau^- \to e^- e^+ e^-$ mode are expected to come from a Bhabha electron or $\tau^- \to e^-\nu_\tau\bar{\nu}_e$ and two electrons from a gamma conversion. The final estimate of the

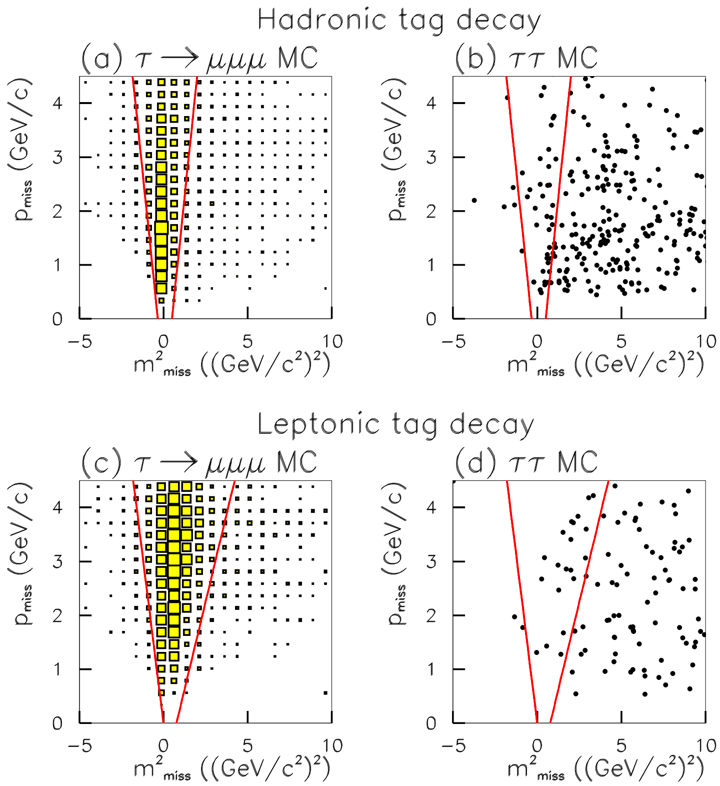

FIG. 3: Scatter-plots of $p_{\rm miss}$ vs. $m^2_{\rm miss}$: (a) and (b) show the signal MC ($\tau^- \to \mu^-\mu^+\mu^-$) and the generic $\tau^+\tau^-$ MC distributions, respectively, for the hadronic tag while (c) and (d) show the same distributions for the leptonic one. Selected regions are indicated by lines.

TABLE II: Summary of $M_{3\ell}$ and ΔE resolutions

Mode	$\sigma^{\rm high}_{M_{3\ell}}$ (MeV/c^2)	$\sigma^{\rm low}_{M_{3\ell}}$ (MeV/c^2)	$\sigma^{\rm high}_{\Delta E}$ (MeV)	$\sigma^{\rm low}_{\Delta E}$ (MeV)
$\tau^- \to \mu^-\mu^+\mu^-$	4.8	5.4	12.5	15.7
$\tau^- \to e^-e^+e^-$	5.1	7.8	13.4	25.1
$\tau^- \to e^-\mu^+\mu^-$	5.1	5.6	12.1	19.6
$\tau^- \to \mu^-e^+e^-$	5.0	6.6	13.4	21.3
$\tau^- \to e^+\mu^-\mu^-$	5.0	6.0	13.3	19.9
$\tau^- \to \mu^+e^-e^-$	5.4	6.7	13.8	23.0

number of the background events is based on the data with looser selection criteria in the $M_{3\ell}$ sideband region, which is defined as the box inside the horizontal lines but excluding the signal region, as shown by the lines in Fig. 4. Assuming that the background distribution is uniform in the sideband region, the number of background events in the signal box is estimated by interpolating the number of observed events in the sideband region into the signal region. The signal efficiency and the number of expected background events for each mode are summarized in Table III.

We estimate the systematic uncertainties due to the lepton identification, the charged

TABLE III: The signal efficiency(ε), the number of the expected background events ($N_{\rm BG}$) estimated from the sideband data, total systematic uncertainty ($\sigma_{\rm syst}$), the number of the observed events in the signal region ($N_{\rm obs}$), 90% C.L. upper limit on the number of signal events including systematic uncertainties (s_{90}) and 90% C.L. upper limit on the branching fraction ($\mathcal{B}$) for each individual mode.

Mode	ε (%)	$N_{\rm BG}$	$\sigma_{\rm syst}$ (%)	$N_{\rm obs}$	s_{90}	$\mathcal{B}(\times 10^{-8})$
$\tau^- \to e^- e^+ e^-$	6.00	0.40 ± 0.30	9.8	0	2.10	3.6
$\tau^- \to \mu^- \mu^+ \mu^-$	7.64	0.07 ± 0.05	7.4	0	2.41	3.2
$\tau^- \to e^- \mu^+ \mu^-$	6.08	0.05 ± 0.03	9.5	0	2.44	4.1
$\tau^- \to \mu^- e^+ e^-$	9.29	0.04 ± 0.04	7.8	0	2.43	2.7
$\tau^- \to e^+ \mu^- \mu^-$	10.8	0.02 ± 0.02	7.6	0	2.44	2.3
$\tau^- \to \mu^+ e^- e^-$	12.5	0.01 ± 0.01	7.7	0	2.46	2.0

track finding, the MC statistics, and the integrated luminosity. The uncertainty due to the trigger efficiency is negligible compared with the other uncertainties. The uncertainties due to the lepton identification are 2.2% per each electron and 2.0% per each muon. The uncertainty due to the charged track finding is estimated to be 1.0% per charged track. The uncertainty due to the e-veto on the tag side applied for the $\tau^- \to e^- e^+ e^-$ and $\tau^- \to e^- \mu^+ \mu^-$ modes is estimated to be the same as the uncertainty due to the electron identification. The uncertainties due to MC statistics and luminosity are estimated to be (0.5 - 0.9)% and 1.4%, respectively. All these uncertainties are added in quadrature, and the total systematic uncertainty for each mode is listed in Table III.

UPPER LIMITS ON THE BRANCHING FRACTIONS

Finally, we open the blind and find no events in the signal region. Since no events are observed in the signal region, we set upper limits on the branching fractions of $\tau^- \to \ell^- \ell^+ \ell^-$. The 90% C.L. upper limit on the number of the signal events including a systematic uncertainty (s_{90}) is obtained from the number of expected background events and observed data, calculated by the POLE program without conditioning [27], which is based on the Feldman-Cousins method [28]. The upper limit on the branching fraction ($\mathcal{B}$) is then given by

$$\mathcal{B}(\tau^- \to \ell^- \ell^+ \ell^-) < \frac{s_{90}}{2N_{\tau\tau}\varepsilon}, \qquad (1)$$

where $N_{\tau\tau}$ is the number of $\tau^+\tau^-$pairs, and ε is the signal efficiency. $N_{\tau\tau} = 492 \times 10^6$ is obtained from 535 fb^{-1} of integrated luminosity times the cross section of the τ pair production, which is calculated in the updated version of KKMC [29] to be $\sigma_{\tau\tau} = 0.919 \pm 0.003$ nb. The 90% C.L. upper limits on the branching fractions $\mathcal{B}(\tau^- \to \ell^- \ell^+ \ell^-)$ are in the range between 2.0×10^{-8} and 4.1×10^{-8} and are summarized in Table III. These results improve the best previously published upper limits [15, 16] by factors from 4.9 to 7.0.

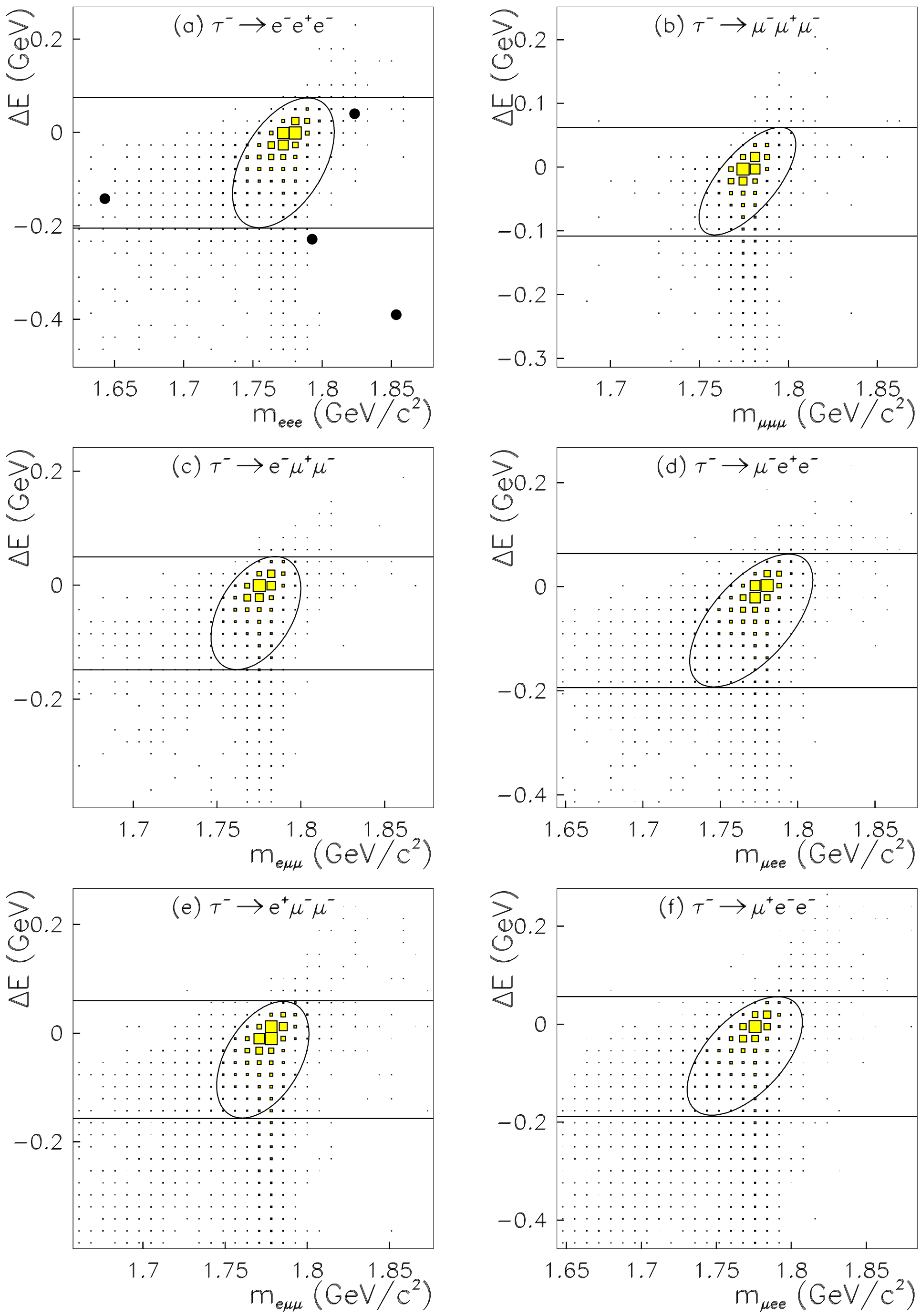

FIG. 4: Scatter-plots in the $M_{3\ell} - \Delta E$ plane: (a), (b), (c) , (d), (e) and (f) correspond to the $\pm 20\sigma$ area for the $\tau^- \to e^- e^+ e^-$, $\tau^- \to \mu^- \mu^+ \mu^-$, $\tau^- \to e^- \mu^+ \mu^-$, $\tau^- \to \mu^- e^+ e^-$, $\tau^- \to e^+ \mu^- \mu^-$ and $\tau^- \to \mu^+ e^- e^-$ modes, respectively. The data are indicated by the solid circles. The filled boxes show the MC signal distribution with arbitrary normalization. The elliptical signal regions shown by a solid curve are used for evaluating the signal yield. The region between the horizontal solid lines excluding the signal region is used to estimate the expected background in the elliptical region.

SUMMARY

We have searched for lepton-flavor-violating τ decays into three leptons using 535 fb^{-1} of data. No events are observed and we set the 90% C.L. upper limits on the branching fractions: $\mathcal{B}(\tau^- \to e^-e^+e^-) < 3.6 \times 10^{-8}$, $\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) < 3.2 \times 10^{-8}$, $\mathcal{B}(\tau^- \to e^-\mu^+\mu^-) < 4.1 \times 10^{-8}$, $\mathcal{B}(\tau^- \to \mu^-e^+e^-) < 2.7 \times 10^{-8}$, $\mathcal{B}(\tau^- \to e^+\mu^-\mu^-) < 2.3 \times 10^{-8}$ and $\mathcal{B}(\tau^- \to \mu^+e^-e^-) < 2.0 \times 10^{-8}$. These results improve the best previously published upper limits by factors from 4.9 to 7.0. These more stringent upper limits can be used to constrain the space of parameters in various models beyond the SM.

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